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DOUBLE-SHELLED TARGET SIMULATIONS WITH LASNEX*

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ABSTRACT

Double-shelled inertial confinement fusion targets in which the outer shell is exploded[1] have been studied with LASNEX. To achieve high DT density, configurations have been found in which the inner shell is ablatively driven by the hot outer shell. Calculations indicate that greater than 100 times liquid DT density can be achieved with the Shiva laser while still retaining some of the symmetry and stability advantages of the single-shelled exploding pusher target. The relative merits of transferring energy to the inner shell by electron conduction and by hydrodynamic work will be discussed.

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Double-shelled inertial confinement fusion targets with an exploding outer shell[1] have been examined as an option for achieving implosion to high density with the Shiva laser. The characteristics of the target lie between the single-shelled exploding pusher and the more efficient ablative targets planned for reactor use. A series of 1-D simulations have been done with the LLL computer code LASNEX.[2] The physics of the target are discussed and some simulation results are presented in this paper. A simple formula which estimates the peak drive pressure is derived.

The Exploding Outer Shell Target

The exploding outer shell target is illustrated in Fig. 1. A DT-filled, thick-walled, spherical inner ball is surrounded by a larger thin-walled outer shell of comparable mass. The outer shell is exploded in the usual exploding pusher sense,[3] i.e., the shell is quickly heated all the way through so that thermal expansion causes half the material to move inward and half to move outward. The inward moving material causes ablation and compression of the inner ball which, in turn, pushes the DT fuel to high density. The inner ball will be called the ablator/pusher.

If a material is to be compressed to high density with a minimum of work, it must be kept cool. A design problem in laser-driven targets is to minimize preheating of the fuel and pusher material by the penetrating suprathermal electrons produced by intense laser light.

Absorbing a given laser power with a relatively large outer shell reduces preheat of the fuel in two ways. First, reduced light intensity

lowers the suprathermal electron energy and range. Second, the increased volume of the target lowers the number density of suprathermal electrons at the surface of the ablator/pusher. Further preheat protection requires that the ablator/pusher wall must have a thickness which is many times the range of the suprathermal electrons. Putting the DT fuel in a relatively small ball allows a thick wall without introducing excessive mass. Also, the thick wall will hold a higher initial DT pressure, reducing the compression necessary to reach a given density.

An easily fabricated design which uses a glass ablator/pusher and a plastic exploding shell is shown in Fig. 2. With 2 TW of peak absorbed power from a 400 ps FWHM Gaussian, the 1-D LASNEX calculation yields 2×10^7 neutrons and gives DT compression to 45 times liquid density.

The Target Implosion Dynamics

The general features of the implosion dynamics are shown in Fig. 3, where the position versus time of several locations in the target material are plotted. The laser pulse reaches peak power just before the imploding half of the outer shell impacts the inner ball. Before this time, suprathermal electrons which are exploding the outer shell are also ablating the outside surface of the inner ball. Thus, the inner portion of the ball (which pushes the DT fuel) is driven by two shock waves. The first arises from the ablation pressure of the suprathermals and the second from the impact pressure of the outer shell material. Depending on the particular design, the first shock may be overtaken by the second either in the ablator/pusher or in the DT, or it may rebound from the center before the second shock arrives.

Figure 4 illustrates the passage of the two shocks through the ablator/pusher for the design of Fig. 2. The pressure and the artificial viscosity for a zone 94% through the ablator/pusher material are plotted versus time. The artificial viscosity is a pressure-like quantity which converts kinetic energy to thermal energy at the shock front in the LASNEX numerical simulation. The rise and fall of the artificial viscosity indicates shock passage and is coincident with the pressure jump caused by the shock. Figure 4 confirms the existence of distinct ablation and impact shocks in the ablator/pusher. The gradual pressure rise before the arrival of the first shock results from preheat by penetrating suprathermal electrons. The sharp pressure rise after the second shock indicates convergence at the target center.

Impact Pressure Estimate

A simple formula has been found to estimate the peak pressure generated in the ablator/pusher material by the impact of the exploding outer shell. It is:

$$P = \frac{E}{24\pi(r_2 - r_1)r_1^2} \tag{1}$$

where E is the energy absorbed from the laser beam at impact time, r_1 is the initial outside radius of the ablator/pusher, and r_2 is the initial central radius of the outer shell. This impact pressure launches the inward-going shock wave discussed above and also stops the inward motion of the outer shell material. The derivation follows.

Rosen and Nuckolls[4] argue from the hydrodynamic continuity equation that when an exploding pusher stagnates against a core, the stagnated mass density will fall off like r^{-2}. For the double-shelled target described here, the core is the ablator/pusher. Assume that at stagnation, half the mass M of the outer shell is distributed like r^{-2} between r_1 and r_2. Then the mass density is:

$$\rho(r) = \frac{M}{8\pi(r_2 - r_1)r^2} \tag{2}$$

For the designs considered here, the shell material is fully ionized. The pressure is 2/3 of the thermal energy density:

$$P = \frac{2}{3}\varepsilon\rho , \tag{3}$$

where ε is the specific thermal energy of the plasma. Assume that half of the absorbed energy E has gone to thermal energy and half to kinetic energy. At stagnation the shell has a nearly uniform electron temperature and not much energy has been transferred to the ablator/pusher, so

$$\varepsilon = \frac{1}{2}\frac{E}{M} . \tag{4}$$

Evaluation of Eq. 3 at $r = r_1$ gives the impact pressure of Eq. 1.

For fixed r_2 and decreasing r_1, the impact pressure increases rapidly since the same impulse from the exploding shell is being

delivered to a smaller ablator/pusher area. The pressure is directly proportional to the temperature of the shell material and hence to the deposited laser energy E. The pressure decreases with increasing shell radius r_2 because the the shell material is spread over a larger volume.

Figure 5 compares Eq. 1 with the peak impact pressure taken from several LASNEX simulations. The absorbed energy is gotten from the simulations at impact time. The agreement is quite good, considering the neglected details of laser light absorption, thermal conduction, and ablator/pusher motion.

Equation 1 is a useful guideline for the design of exploding outer shell targets. Within 10%, the maximum average DT density for the simulations of Fig. 5 was directly proportional to the peak impact pressure.

An Improved Ablator/Pusher

The glass ablator/pusher is a poor attenuator of suprathermal electrons. When the glass is thin, the inner pusher layers are heated so much that they expand and cause the DT fuel to be compressed, heated, and stagnated before the impact-driven shock can penetrate the ablator/pusher. In this mode the inner ball itself acts as an exploding pusher and no usful work is done by the outer shell. This problem worsens with increasing laser wavelength since the suprathermal electron range varies nearly quadratically with λ. When the glass is made thicker, too much energy is lost in the ablator/pusher.

The performance of the exploding outer shell target as measured by both neutron yield and maximum compressed DT density can be improved by

going to a higher-Z, higher-density ablator/pusher. For a given ablator/pusher mass, an increase in Z reduces suprathermal electron penetration by increased scattering from ions. Furthermore, an increase in density reduces thickness and hence shock penetration time.

Figure 6 shows a design with a copper ablator/pusher. The LASNEX calculation gives a peak DT density of 50 g/cc, about 250 times liquid density. A comparison with Fig. 2 shows that the copper design achieves 5 times higher density and 10 times more neutron yield than the glass design. The radius versus time plot in Fig. 6 shows clearly the two shock waves in the copper ablator/pusher.

Radiochemistry Density Diagnosis

The DT density at fusion reaction time in the above designs can be diagnosed by radiochemistry.[5] As the neutrons produced by thermonuclear reactions in the DT fuel leave the target, they may produce radioactive isotopes in the pusher material. The number of these neutron activations is proportional to the neutron yield and $\int \rho dR$ of the pusher material. Since hydrodynamics connects the $\int \rho dR$ of the pusher with that of the compressed DT, it is possible to infer the compressed DT density from a measurement of the neutron activation level and an independent measurement of the neutron yield. Both silicon and copper have suitable neutron activation reactions for this radiochemistry diagnostic procedure.[5] As indicated in Figs. 2 and 6, the LASNEX calculations predict unambiguous radiochemistry signals for determining the compressed DT density.

A Design Less Sensitive to T_{HOT}

The 1-D designs presented here have been optimized for a given laser pulse. This optimization is dependent on the physics modeling in LASNEX. An important uncertainty in the present modeling is the calculation of the production and transport of suprathermal electrons. The brute force method of overcoming these uncertainties would be to repeat the optimization procedure with real laser experiments. An alternative is to find a design that is less sensitive to the uncertainties.

Variations in the suprathermal electron physics affect the strength and timing of the two shocks in the ablator/pusher. For example, an increase in the suprathermal electron temperature T_{HOT} strengthens and advances the ablation shock, but delays and weakens the impact shock.

A design selected for its insensitivity to T_{HOT} is shown in Fig. 7. The ablator/pusher is glass with a thin coating of gold. The relatively thick, low density glass controls the propagation time of the first shock. The thinner, high-Z, high-density, gold layer provides most of the suprathermal electron attenuation. The impact shock arises in the gold and catches the ablation shock in the glass layer. Thus, a single strong shock drives the DT fuel. Variation of T_{HOT} changes the position in the glass where the two shocks merge, but only weakly affects neutron yield and maximum DT density.

Discussion

The exploding outer shell design provides a bridge between exploding pushers and ablatively-driven targets.

The single-shelled exploding pusher target achieves high neutron yield by heating DT gas to a high temperature at low density. Because the shell explodes, it is inherently resistant to the Rayleigh-Taylor instability. Furthermore, departures from spherical symmetry in shell fabrication and in laser illumination are reduced by hydrodynamic expansion and by heat conduction. However, the exploding pusher is prohibitively wasteful of energy when considered as a reactor target.

Ablatively-driven targets reduce the amount of energy needed to compress DT to thermonuclear ignition conditions. Simulations of efficient double-shelled targets for reactor application have been described by Lindl.[6] In these targets a thick outer shell is imploded by ablation of its outer surface. The relatively cool, dense inwardly moving material collides with the inner shell and transfers energy by hydrodynamic work. Special care is required to insure the necessary illumination symmetry and to control the growth of Rayleigh-Taylor instabilities.

The characteristics of the exploding outer shell target lie between those of the exploding pusher and those of the ablatively-driven reactor targets. Its outer shell has the symmetry and stability of the exploding pusher, but the thick inner shell allows a cooler, higher density fuel implosion more characteristic of a reactor target.

The outer shell material that impacts the inner ball is hot and at low density so that more energy is transferred by electron thermal conduction than by hydrodynamic work. Two-dimensional calculations show that the impact shock can be much more spherical than the collision interface between the shells.

In conclusion, exploding outer shell target simulations for SHIVA give diagnosible DT densities that are one or two orders of magnitude higher than so far achieved in laser experiments. The target is expected to be tolerant of the practical difficulties in fabrication and laser illumination. It offers a significant experimental step toward an efficient reactor target.

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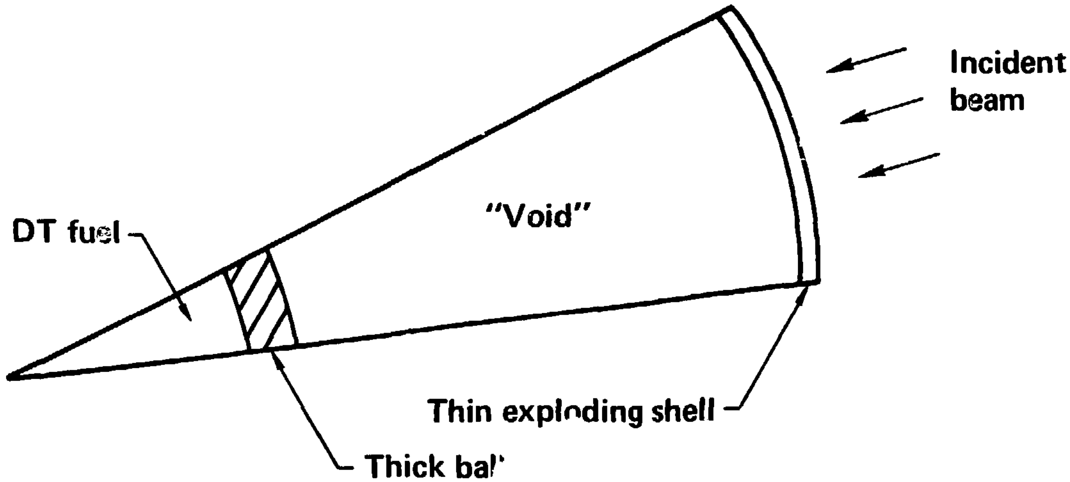
THE DOUBLE-SHELLED TARGET WITH AN EXPLODING OUTER SHELL



Properties

1. Retains symmetry and stability of exploding pusher
2. Resistant to suprathermal electron preheat
3. Density can be diagnosed by radio chemistry
4. Higher DT density than exploding pusher

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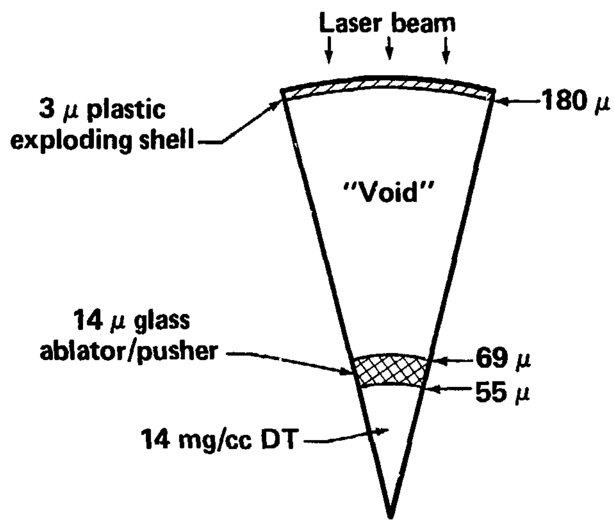
Fig. 1

EXPLODING OUTER SHELL HIGH DENSITY DESIGN



LASNEX 1-D calculation for SHIVA

Laser (1.06 μ):	400 ps Gaussian 2 TW absorbed (collisionless absorption)
Peak pusher velocity:	18 cm/μs
Yield:	2×10^7 neutrons
Peak DT density:	9 g/cc
Peak glass ρR:	0.025 g/cm^2
Rad chem counts:	100 (background 2)

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Fig. 2

After an initial ablation by hot electrons, the fuel ball is driven by the impact from the exploded outer shell.

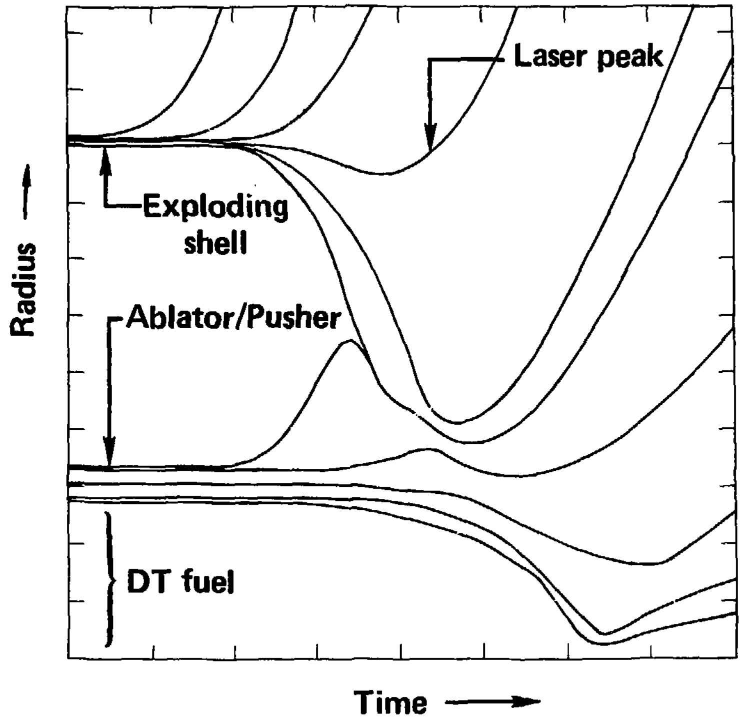

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Fig. 3

PRESSURE VS TIME SHOWING SHOCKS IN THE GLASS ABLATOR/PUSHER NEAR THE FUEL INTERFACE

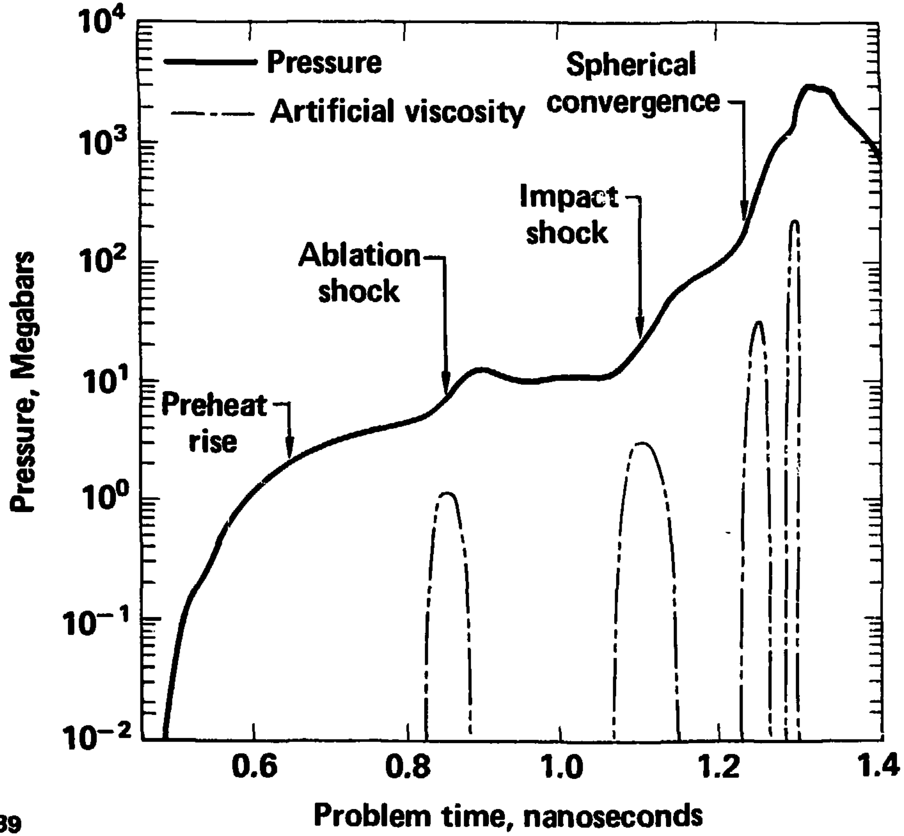

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Fig. 4

PEAK IMPACT PRESSURE VERSUS ABLATOR/PUSHER RADIUS

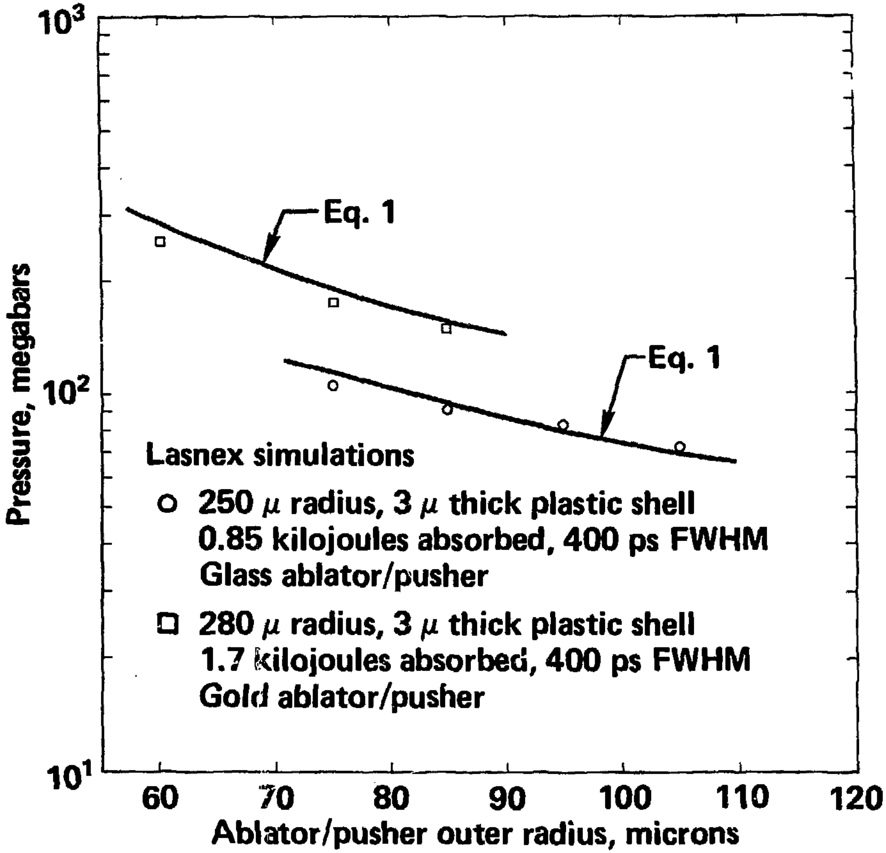

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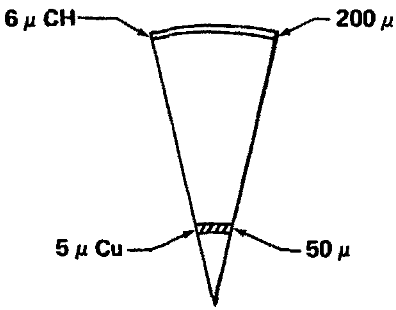
Fig. 5

BETTER PERFORMANCE WITH HIGHER z, HIGHER ρ ABLATOR/PUSHER

- Higher z → better preheat protection
- Higher ρ → better compression

Laser	300 ps, 2 TW absorbed
Yield	2×10^8 neutrons
Peak DT density	50 g/cc
Peak Cu ρR	0.09 g/cm^2
Rad chem counts	6000 (background 10)



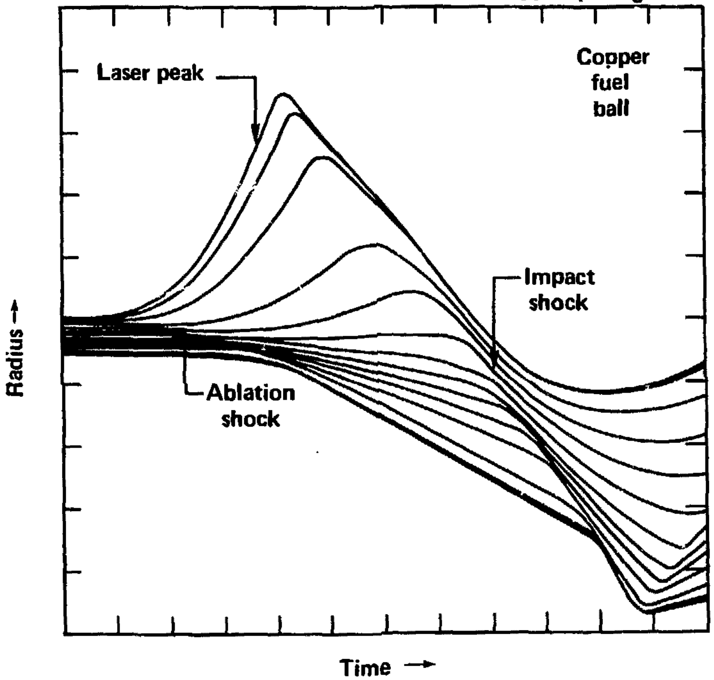


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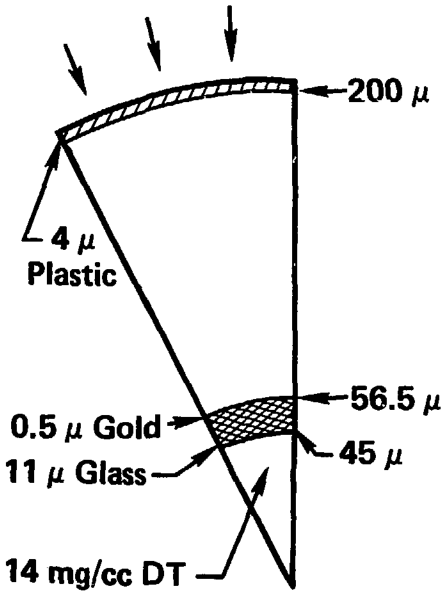
Fig. 6

A TARGET DESIGN THAT IS LESS SENSITIVE TO UNCERTAINTIES IN SUPRATHERMAL ELECTRON PHYSICS

Ablation and impact shocks merge somewhere in the glass. Neutron yield and peak DT density only weakly dependent on where.



LASNEX 1-D calculation for SHIVA

Laser (1.06 μ):	400 ps Gaussian 2 TW absorbed
Peak Pusher Velocity:	23 cm/μs
Yield:	4×10^{8} neutrons
Peak DT Density:	25 g/cc
Peak Glass ρR:	0.045 g/cm^2
Rad chem counts:	3600 (backgrd. 2)

50-60-1078-3788

Fig. 7